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Design and Development of Piezoelectric Actuators and Motors at Garman Systems

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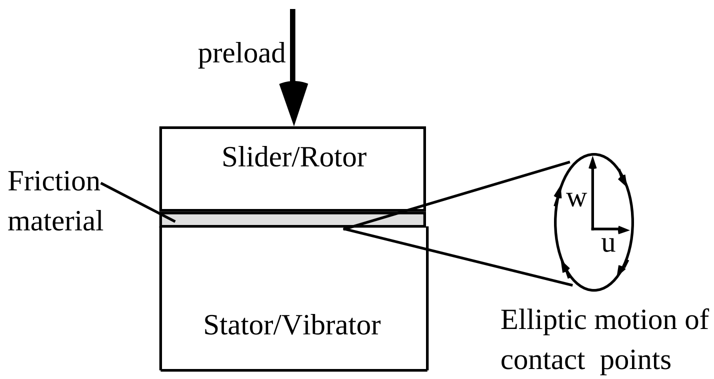
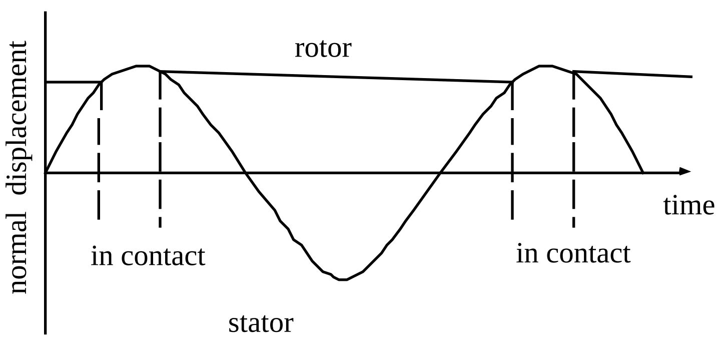
GSi Resonant (Ultrasonic) Motors





- Piezoelectrics generate an elliptic motion on the surface of the stator.
- A rotor/slider is pressed to the stator.
- Because of the difference in time constants, the rotor is contacted intermittently.
- The slider is driven by the tangential motion of the ellipse.
- The force is determined by friction and the normal component of the ellipse.
- Velocity and direction are controlled by phase or voltage.

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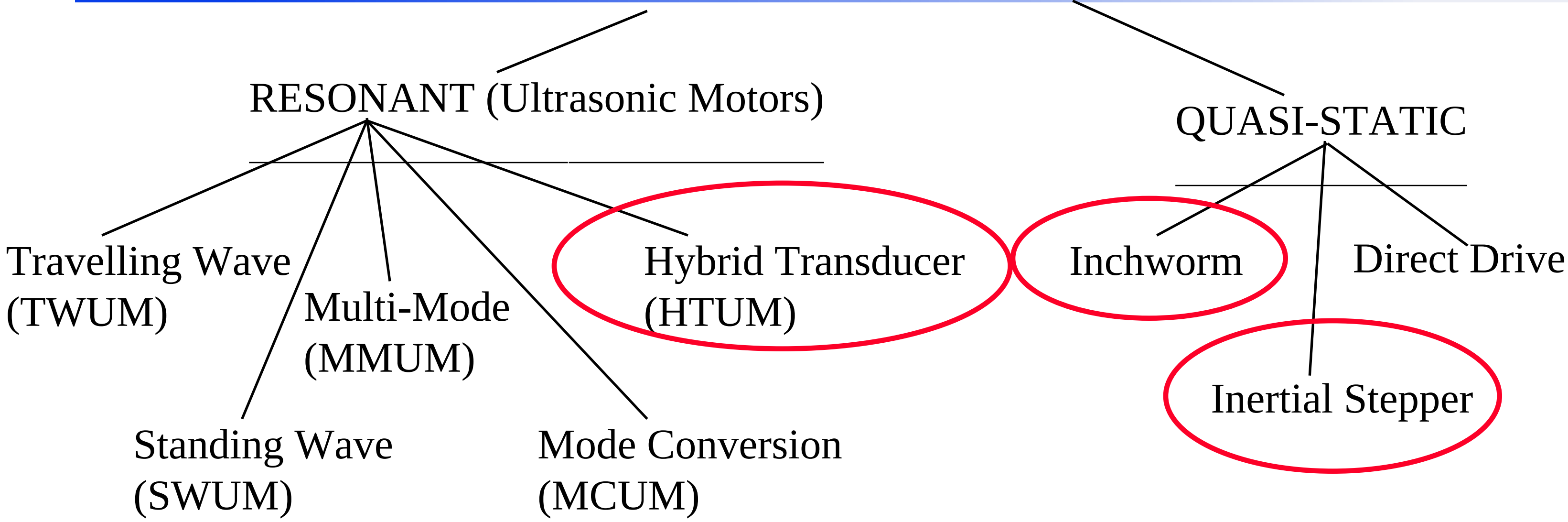
GSi Motor Concepts



- Inchworm
  - Designed in ability to operate at high frequency w/o wear
  - Uses high stroke piezo clamping devices to compensate for wear and tolerances
- Stick/Slip Stepper Motor (modified inertial stepper)
  - Kinetic - Static friction drive
- Hybrid transducer ultrasonic motor (HTUM)
  - Designed with micro-positioning capability

The need for amplification

- Piezoelectric stacks have high force, high resonance frequency, and high power density, but very small stroke
  - The stacks have a blocked force of 850 N and a resonance frequency of 7 kHz
  - The stacks can produce strains of 0.1%

- The segment requires 100μm of piston motion, this would necessitate a 100mm tall stack

- Amplification flexure mechanisms can increase the motion of the stack to the required level

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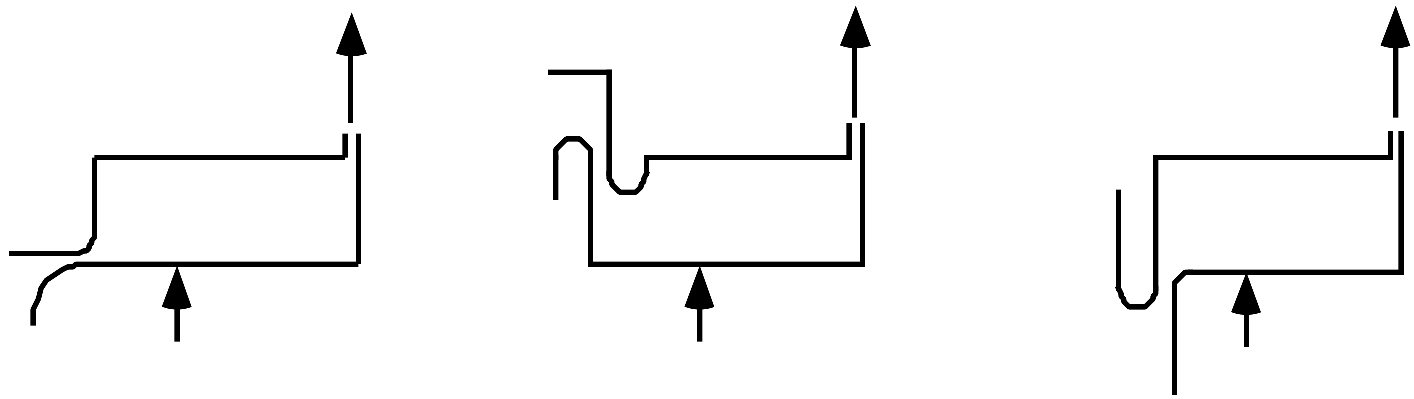
Optimal Flexure Orientation



- When input force is applied, flexure is put in:
  - Case 1. Shear
  - Case 2. Compression
  - Case 3. Tension
  -
- Through an iterative process, Case 3 has been proven to be most efficient for our flexure mechanisms

Flexure-Stack Mechanical Interface

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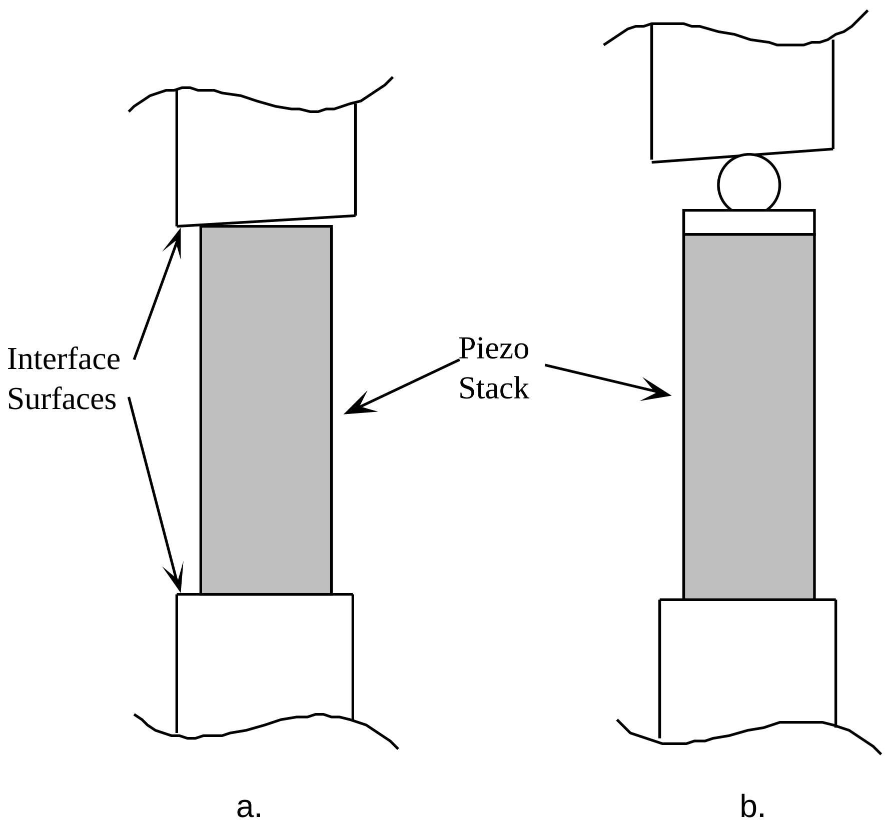

- Piezo stacks work best when subjected to compressive loads applied vertically to the center of the stack
- Loads applied off-center can damage the stack
- A steel sphere provides an ideal interface
  - The sphere keeps loads applied on the center axis of the stack
  - The sphere is not affected by small surface variations where the stack interfaces the flexure

Flat Plate Mechanism

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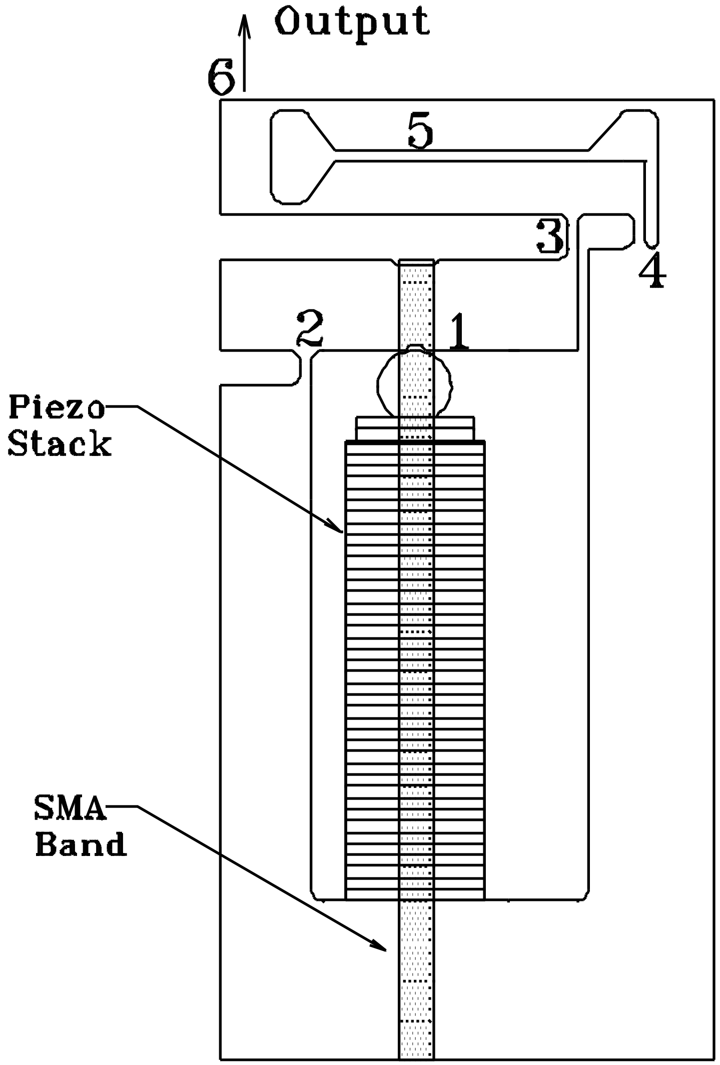

- The detail shown is cut with a wire EDM machine
-
- Critical dimensions:
- Height: 45.5 mm
- Width: 30 mm
- Thickness: 5 mm

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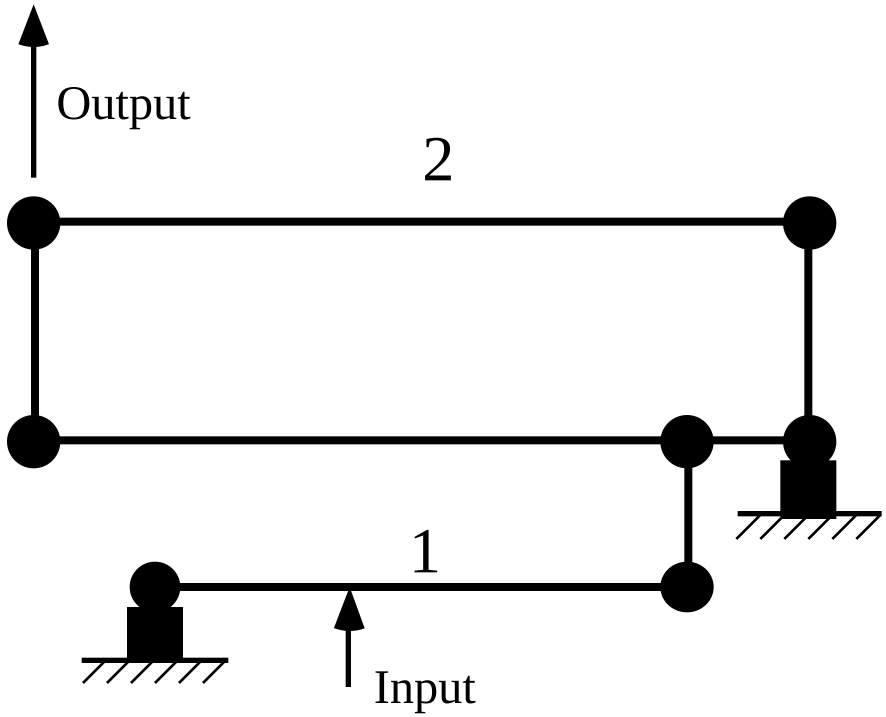
Kinematic Analysis



- The linkages are considered to be rigid bodies for kinematic analysis
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- Stages 1 and 2 are cantilevered beams
-
- Stage 2 contains a four bar parallel linkage, to insure vertical motion
-
- The ideal kinematic amplification factor of the flat plate mechanism is 12.7

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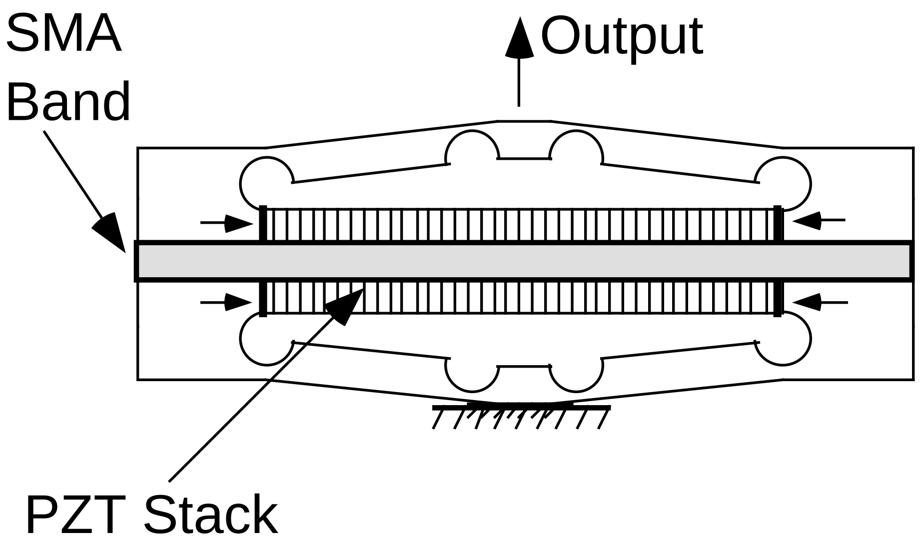
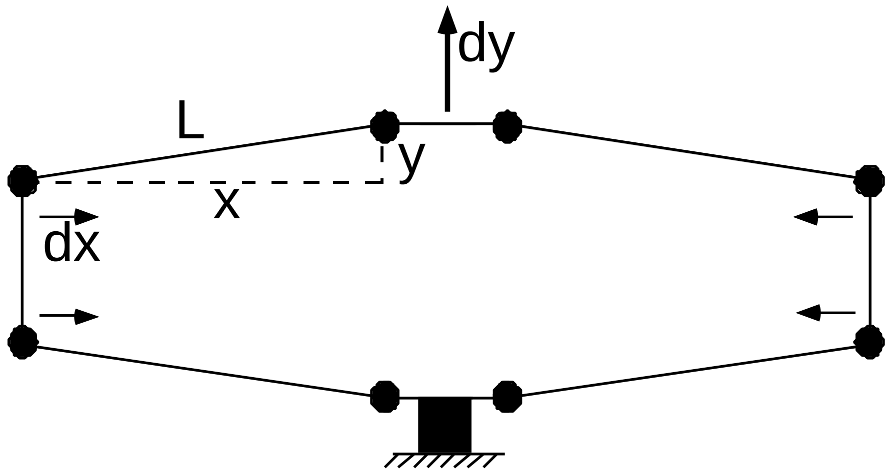
BOA Mechanism



- The mechanism is cut from a single piece of steel using wire EDM
- The output displacement is controlled by the expansion of the piezo stack
- Output force is dependent on the SMA band and the stiffness of the flexure
- Critical dimensions:
  - Length: 27 mm
  - Height: 11 mm
  - Depth: 5 mm

GSi Kinematic Analysis



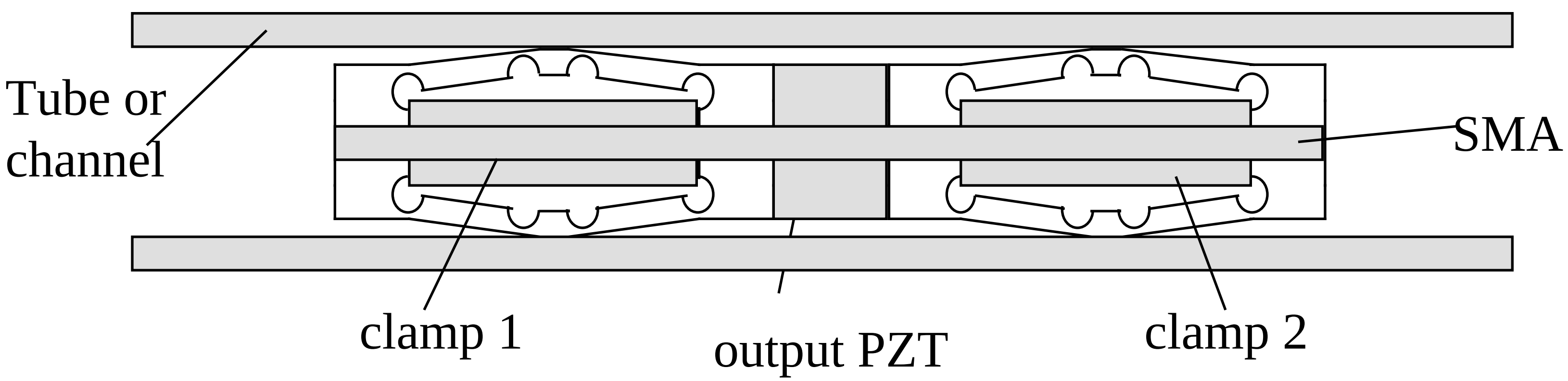
- The linkages are considered to be rigid bodies for kinematic analysis
- The equation governing the ideal output is:

$$dy = \frac{x}{y} dx$$

- The kinematic amplification factor is 9X for the configuration shown

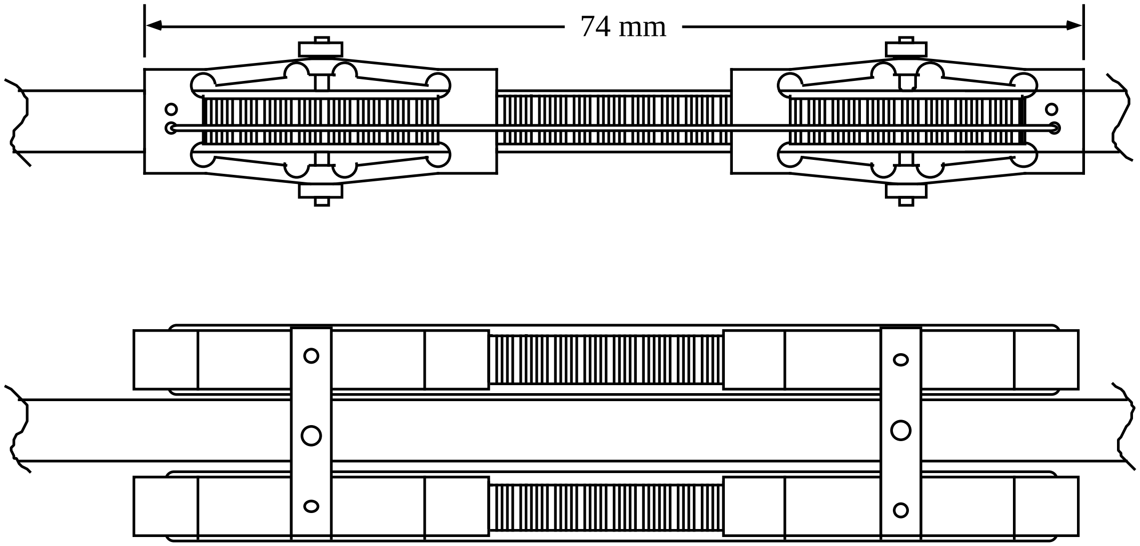
BOA Inchworm (in channel)

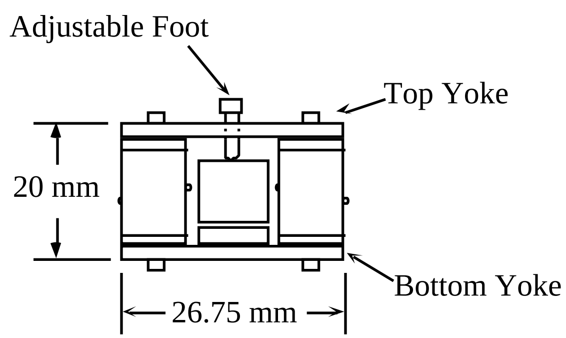
- Use BOA type actuator to get clamping motion
  - Compact clamping actuator with minimal non-active material
  - Long stroke of BOA allows compensation for manufacturing tolerance and thermal expansion/contraction
- Design offers limited ability to make electrical or mechanical adjustments



BOA Inchworm (on shaft)

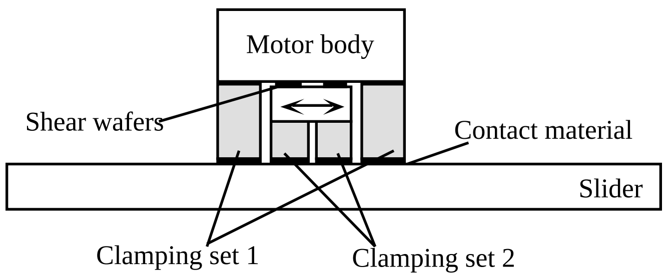
- Pairs of BOA type actuators mounted around a shaft
  - Each pair of BOAs connected with top and bottom yokes
  - Adjustable foot used to compensate for manufacturing tolerances and thermal expansion/contraction
- Longer extension stacks yield larger step sizes and greater motor speed

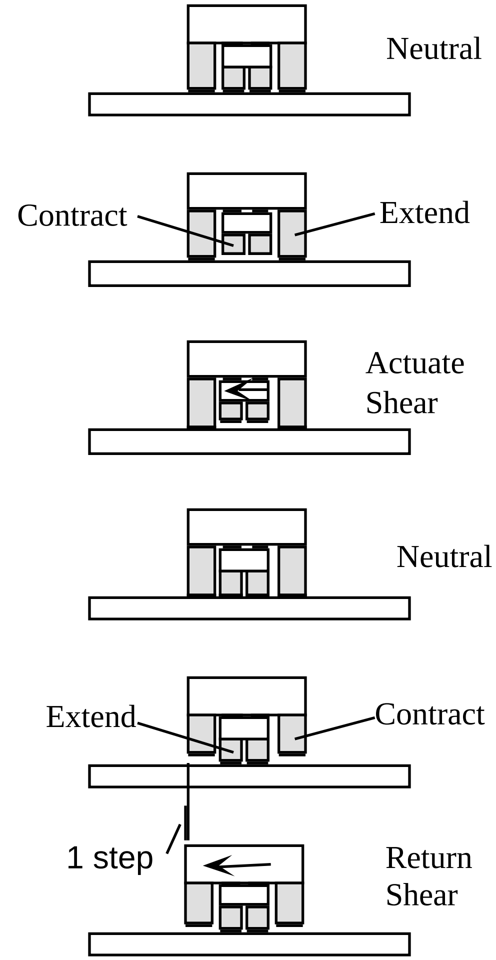




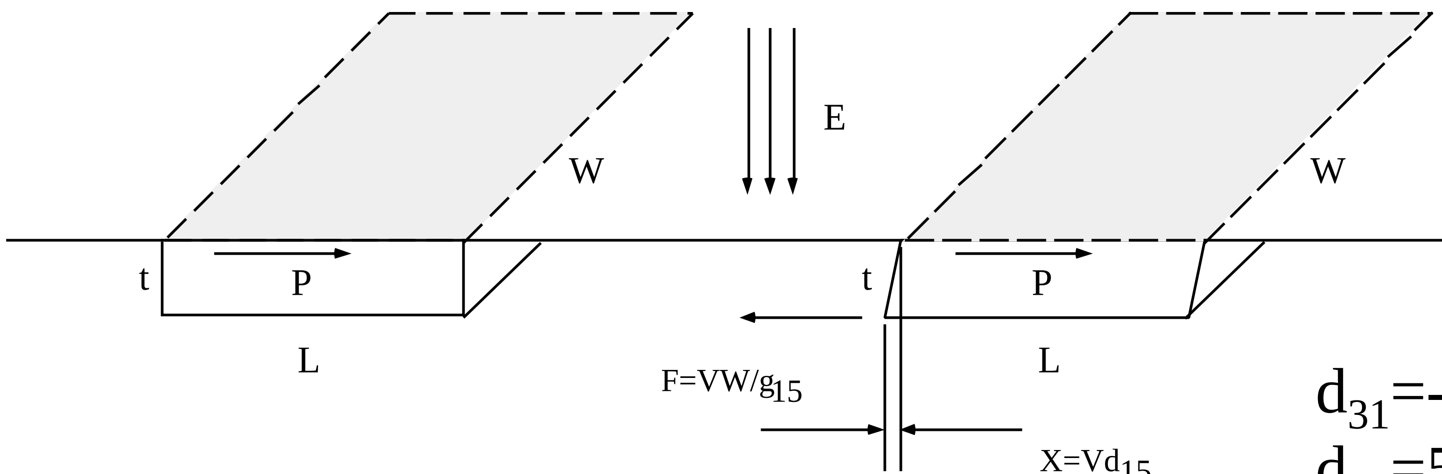
GSi Differential Stroke Inchworm Motor

- Eliminate assembly tolerance issue
  - preload a “stator” to a shaft
  - rely on the difference between the extension and contraction of stack actuators
  - wear is automatically compensated for
  - can be run at high frequency
- Use shear wafers for output





GSi Piezoelectric Shear Wafer



d_{31}=-275e-12 m/V
d_{33}=590e-12 m/V
d_{15}=670e-12 m/V

- Advantages of shear wafers
  - High positive and negative voltage limits
    - Limited by the dielectric breakdown in both directions
  - Does not depole easily, minimal aging.
  - Can be stacked.

Scalability Considerations for Inchworm Motors

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Tolerance and assembly

- Static displacement of a piezo-actuator is used for clamping and releasing
- Dimensional tolerances must be less than the maximum stroke of the piezo-actuator
  - The slider/clamp interface must be “smooth” in order to avoid stalling
- Lever arm stoke amplification mechanisms have be used to address these limitations on miniaturization

Wear

- Operation well below resonance minimizes wear
  - higher frequency operation introduces dynamics of the clamping and extension mechanisms and increases wear
  - Small motors can be operated at high frequency with out exciting motor dynamics
- Differential stroke compensates for wear through preload

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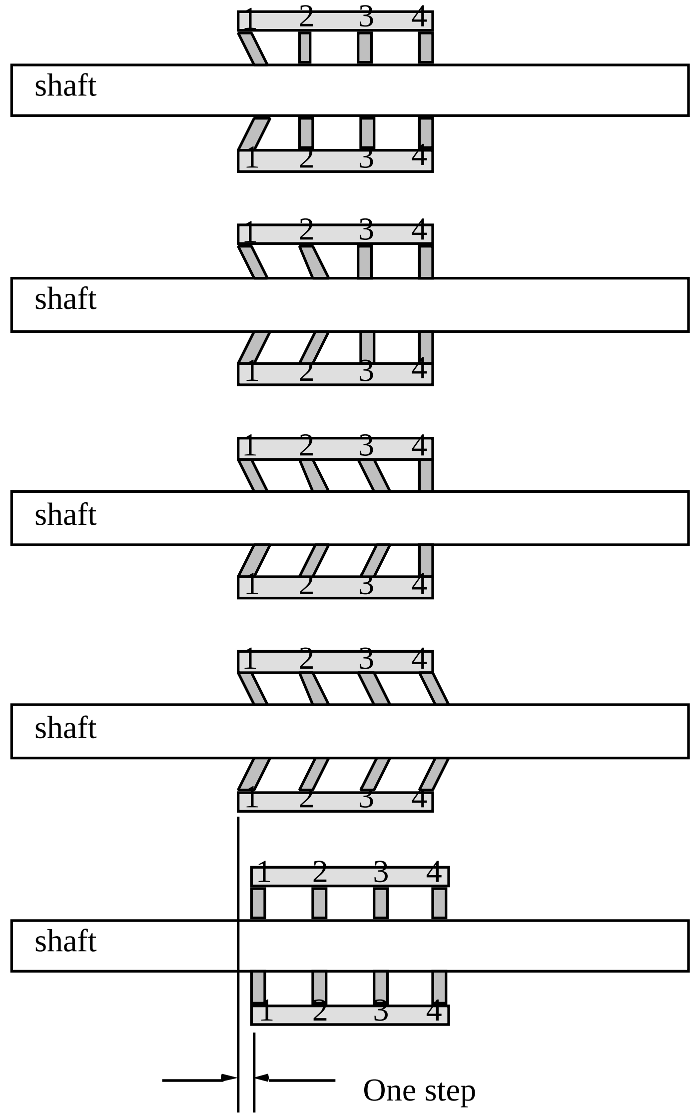
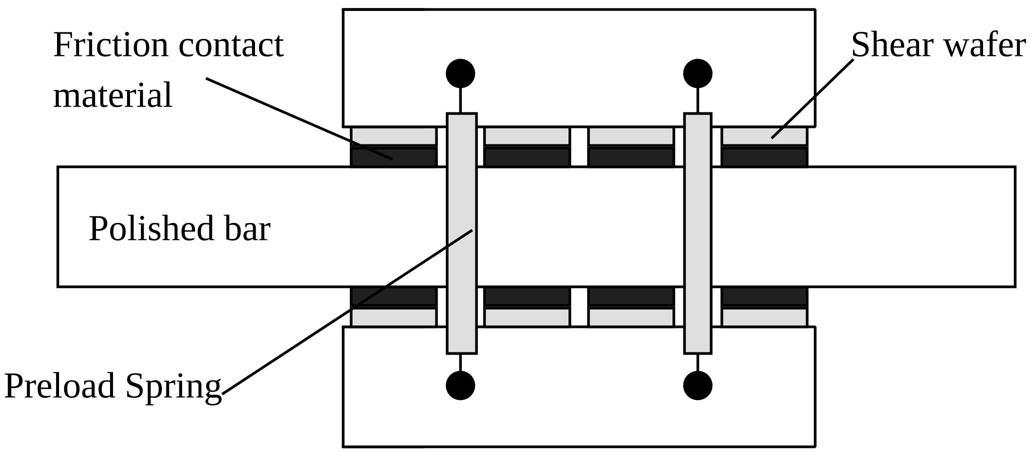
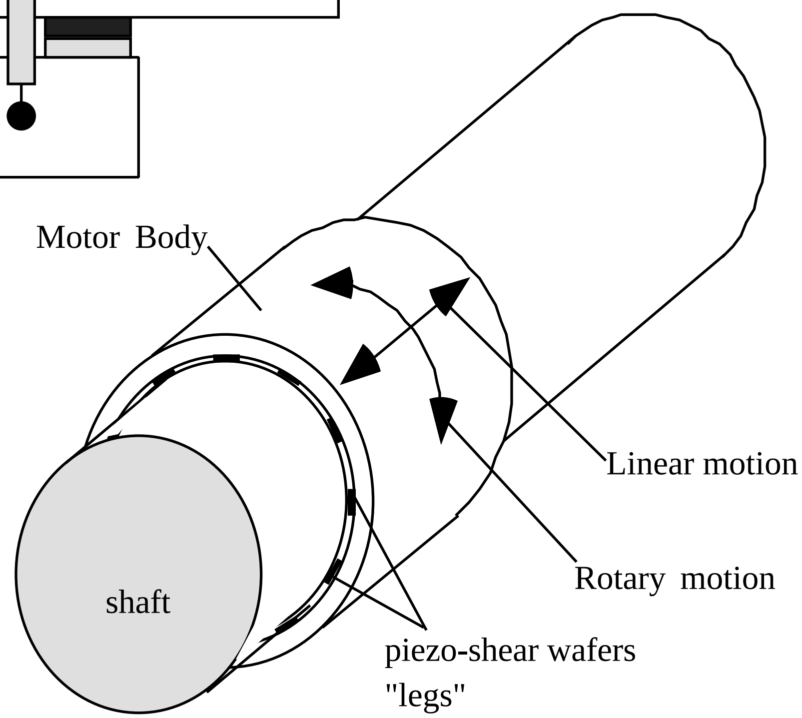
Stick/Slip Stepper - Operating Principle

- Piezo shear wafers operate in sequence shown
- Single leg moves because kinetic friction is less than holding force of other legs (kinetic < static)
- Precision micro-positioning accomplished by activating all legs together
- Shear wafers can be stacked to improve speed at the cost of force (displacement per cycle increases)



Stick/Slip Stepper Motor





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Stick/Slip Stepper Design Issues

- Contact uniformity is critical
  - can be addressed through the use of a compliant backing
- Amplifier slew rate
  - high slew rate is required to ensure that the feet break into kinetic friction
- Contact material choice is critical
  - high static friction coefficient & low kinetic friction coefficient
- Can be made completely non-magnetic
  - ceramic or plastic body, run on a ceramic shaft
- Simple design makes this motor very scaleable
- Potentially low cost, versatile linear motor
  - provided that further development research proves successful

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Pharaoh's Motor

- Utilizes strain in an elastic medium to store energy.
- Force and displacement of each individual actuator accumulate to provide smooth motion for the motor.
- Force required from individual actuator is much less than force output of the motor.

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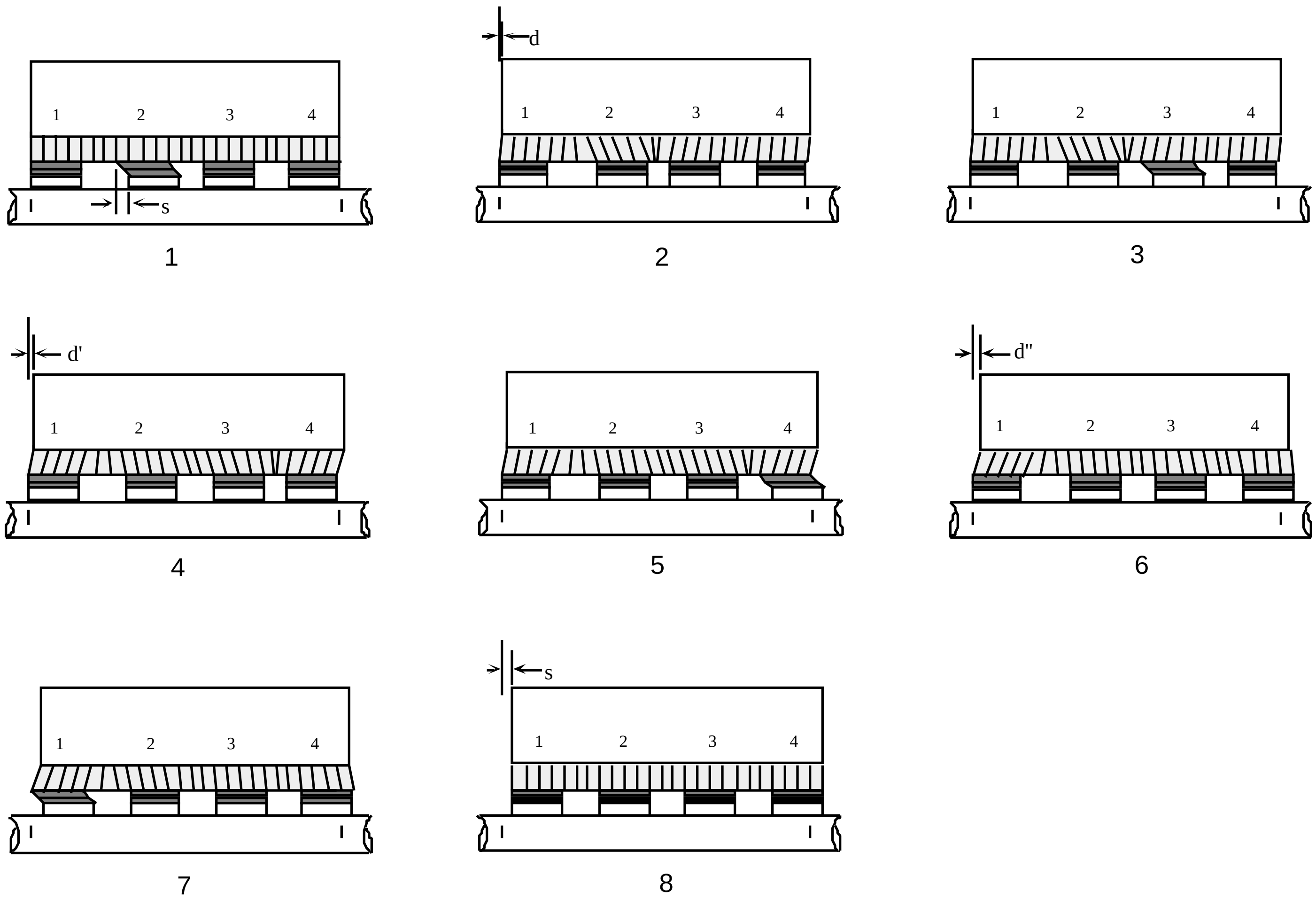
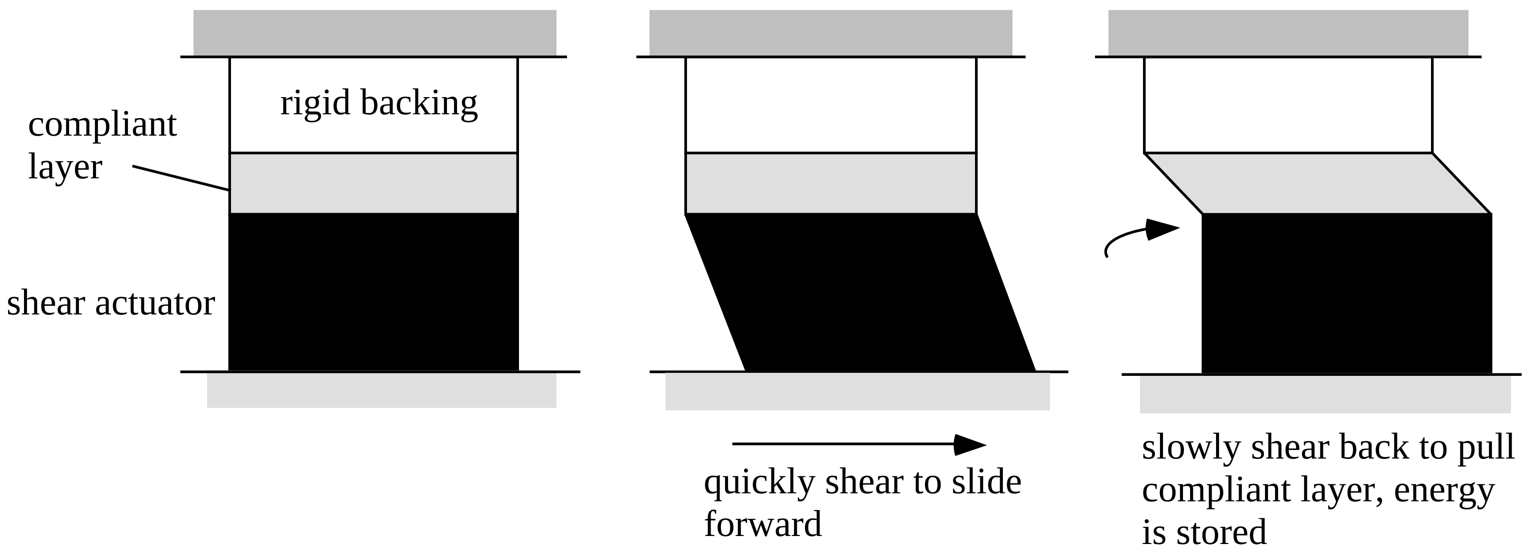
Pharaoh's Motor stepping sequence



Pharaoh’s Motor

- Feasibility study of one Pharaoh’s motor ‘foot’



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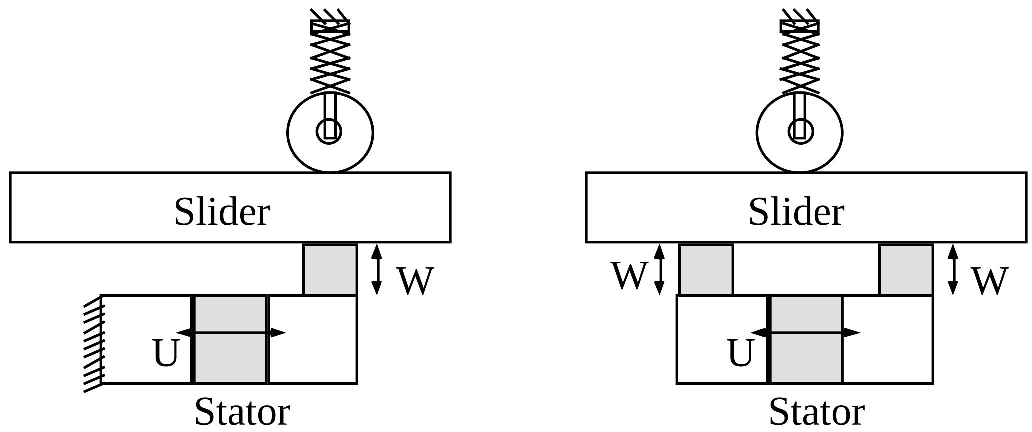
Hybrid Transducer (HTUM)



One contact point

Two contact points

- Elliptic motion is generated by two orthogonal piezo-vibrators
- Operate at resonance of output, U
- Separation of elliptic motion into two controllable components allows performance and design flexibility
- Easier to miniaturize
- Can tune both resonance frequencies to get best performance

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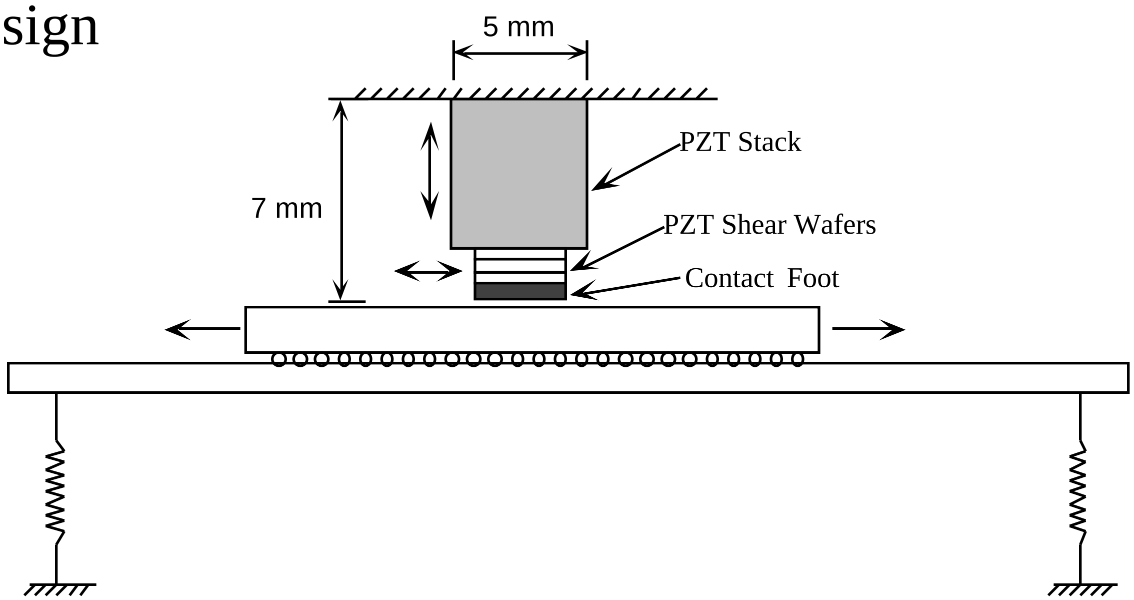
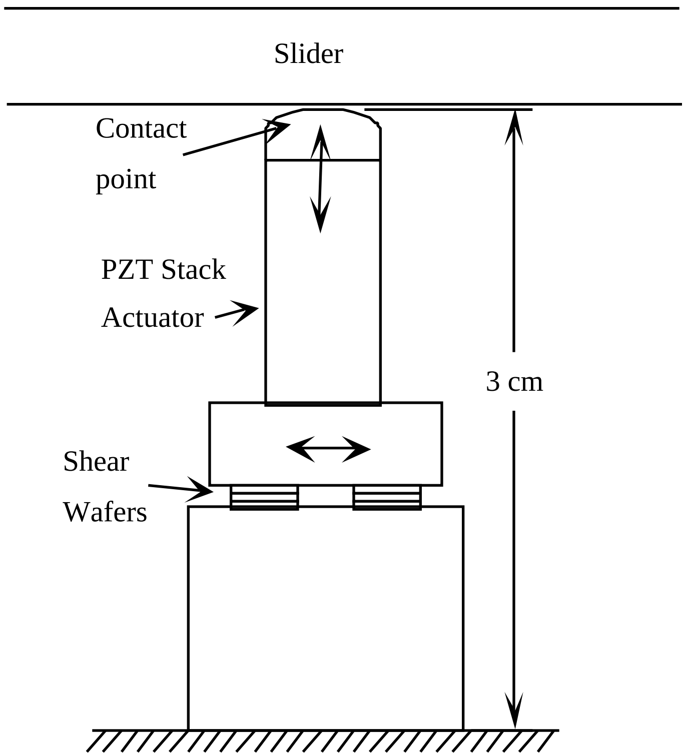
Shear Stack HTUM

- Elliptical motion is created using shear wafers, and a linear stack actuator, running 90° out of phase
  - The linear stack is 5 x 5 x 5 mm, capable of displacing 4μm
  - 4 shear wafers are hand stacked
- The contact foot is covered with Kapton film to prevent ultrasonic welding
- Resonant frequencies above 20 kHz because of its low mass
- Extremely compact design



GSi Modified Shear Stack HTUM

- The added mass that the shear wafers move lowers the resonant frequency
- The linear stack actuator is 10x5x5 mm, capable of displacing 9 µm
- Two shear stacks provide horizontal motion
- The resonant frequency is lower than 20 kHz, the maximum frequency that can be achieved with the quadrature oscillator chip



Modified Shear Stack HTUM: Test Results

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- The stator was placed on a translation stage and pushed against a slider mounted on compression springs for testing
- Results:
  - Frequency: 18.1 kHz
  - Shear stack input: 92 Vpp
  - Linear stack input: 39 Vpp
  - Static holding force: 4.4 N

Load (N)	Speed (mm/s)
Unloaded	32
0.49	22
0.98	12

- Increased performance can be achieved by operating multiple stators in parallel

Orthogonal Stack HTUM

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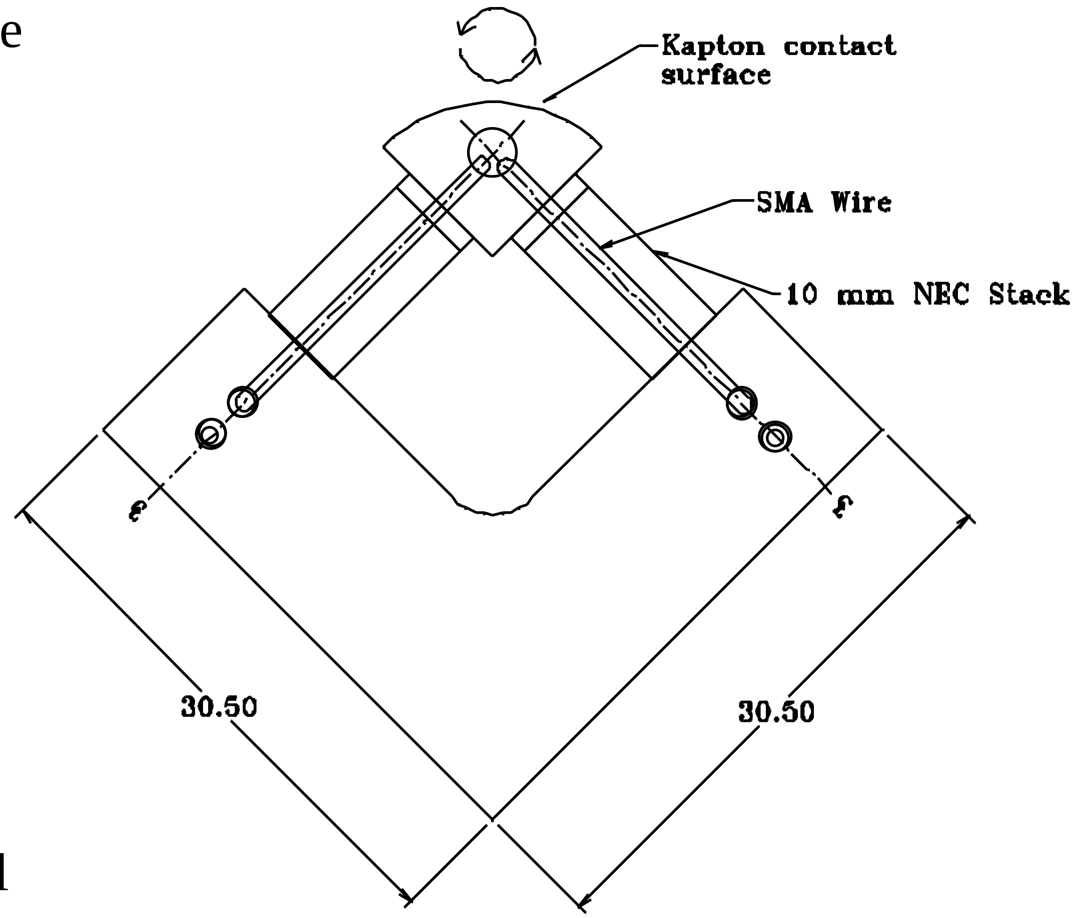
- Operation of the stack actuators with sine waves 90° out of phase creates elliptical motion at the contact point
  - The input signal is generated by a quadrature oscillator chip
- The stack actuators can achieve a 9μm displacement with a voltage input of 150 Vpp
- The stack actuators are held in place using super-elastic Nitinol



(Dimensions in mm)

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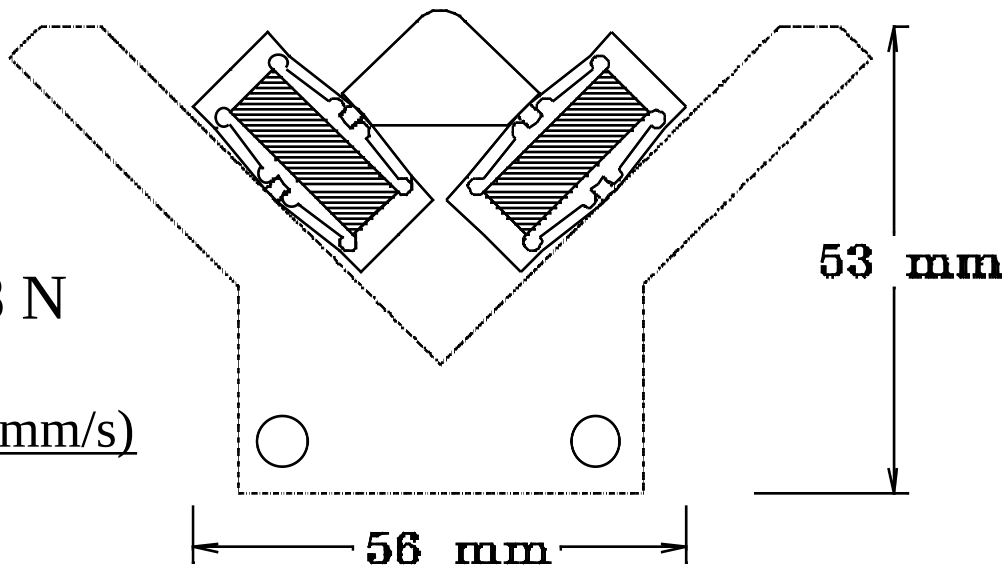
BOA HTUM

- The principle of operation is the same as in the orthogonal stack HTUM, with the addition of the BOA mechanism
- The BOA mechanism provides amplification, increasing speed and load carrying capability
  - The BOA mechanism increases the stepsize of the motor
  - Steel BOAs are used for increased stiffness
  - The BOAs are preloaded with superelastic Nitinol
- Because of the amplification, the resonant frequency is much lower than with the other HTUMs
- The BOA HTUM is run as the orthogonal stack motor with two sine waves 90° out of phase

GSi BOA HTUM: Test Results

- The BOA HTUM is run by advancing the motor with a translation stage to contact a slider mounted on compression springs
- Results:
  - Frequency: 1kHz
  - Input: 80 Vpp
  - Static holding force: 9.8 N

Load (N)	Speed (mm/s)
Unloaded	13
0.49	10
1.47	3.7
2.45	2.2



GSi HTUM Future Development Issues

- The motors operate best at resonance, but the frequency of the resonance changes with the motor normal force, temperature, and operating voltage
- Accurate analysis of the movement of the contact point of the stator and the slider requires a measurement system such as a laser vibrometer
- A higher frequency quadrature oscillator will be needed for miniaturization
- The HTUMs can operate with multiple stators
- The prototypes built show potential for several different designs

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Summary

- Garman Systems has diverse experience in piezoceramic based actuators and motors
  - Axial and transverse flexure based actuators
  - Linear and rotary inchworm designs
  - Stick/slip motor designs
  - HTUM designs
- The Pharaoh's motor represents a novel piezoelectric drive mechanism
  - work in progress